Space charge studies and comparison with simulations using the FNAL Booster

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Abstract. We present measurements of transverse and longitudinal beam phase space evolution during the first thirty turns of the FNAL Booster. We discuss the experimental techinque, which allowed us to obtain turn-by-turn measurements of the beam profile. We then compare our results with the prediction of the Synergia 3D space charge simulation code.

1. Introduction

The Fermilab Booster is a rapid-cycling, 15 Hz, alternating gradient synchrotron with a radius of 75.47 meters. The lattice consists of 96 combined function magnets in 24 periods, with nominal horizontal and vertical tunes of 6.7 and 6.8 respectively. The Booster accelerates protons from a kinetic energy of 400 MeV to 8 GeV, at a harmonic number h=84, using 17 rf cavities with frequency which slews between 37.7 MHz (at injection) and 52.8 MHz (at extraction). The revolution time at injection is 2.2 μ s. A comprehensive technical description of the Booster as built can be found in reference [Booster Staff]. The injection system utilizes the H^- charge-exchange injection technique [Ankenbrandt]. The typical linac peak-current is 45 mA; usually up to ten turns of H^- beam are injected in the booster. The injected beam is a stream of bunches equally spaced at the linac rf frequency of 201.2 MHz. During injection, a pulsed orbit bump magnet system (ORBUMP) is used to superimpose the trajectories of the circulating (protons) and injected (H^-) beams.

There are many factors affecting the behavior of the Booster beam, including the energy and emittance of the incoming beam, nonlinear field errors and space charge effects, which is believed to be responsible for a significant fraction of the observed losses in the Booster [Popovic], during the first 2 ms of the cycle (injection, capture, and bunching phase). In general, space charge effects are recognized as one of the most important problems which limit the total number of particles in a low energy proton synchrotron. Since the performance of the Booster is what makes or breaks the current (MiniBooNE experiment) and future (MINOS experiment) FNAL neutrino programs, and its stable operation is required for the current FNAL collider program, it is essential to study and quantify these effects. In order to achieve this goal, we have developed a full three dimensional (3D), Particle In Cell (PIC) model of the booster, based on the package *Synergia* [Amundson]. The *Synergia* package has been developed under the DOE SciDAC initiative for accelerator modeling *Advanced Computing for 21st Century Accelerator Science and Technology*. Synergia incorporates existing packages for modeling 3D space charge and computing transfer maps using Lie algebraic techniques. It utilizes a split operator technique for particle propagation, includes a

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parser of the *Methodical Accelerator Design* (MAD) language, and has multi-turn injection modeling capabilities. The code has the capability to compute higher order transfer maps, but linear maps were used for the simulations presented in this paper.

One of the most important tasks in the process of studying the performance of a real accelerator using a simulation is to establish the validity of the model, by comparing the prediction of the simulation to that of data from experiments with well defined initial conditions. This is a very complicated process, since it not only involves a large number of different parameters that should be kept under control, but also requires very good understanding of the instrumentation used to perform these measurements. In the following sections, we will describe the first steps of such a validation process for the *Synergia* package, using data taken with the FNAL Booster.

2. Experimental Data

The objective of the experiment was to study the beam evolution in the first few turns after injection, by comparing beam widths (both transverse and longitudinal) to the simulation as a function of time, with single turn resolution, and for different beam currents. The FNAL Booster has two measuring devices capable of measurements of beam widths with single turn resolution: the *Ion Profile Monitor* detector (IPM) [Zagel], which utilizes the ions from ionization of the residual gas by the proton beam to measure transverse beam profiles, and the *Resistive Wall Monitor* (RWM) device, which utilizes the induced current on the beam pipe by the particle beam, to measure the longitudinal beam profile. Since the response of the IPM depends on the charge of the beam, and since the goal of the experimental program is to use this detector for a quantitative study of space charge effects, we installed a third measuring device, in order to check and calibrate the performance of the IPM. This device utilizes a single wire placed just outside the beam envelope of the displaced beam orbit at the injection region. To obtain single turn time resolution, we use a "flying beam" rather than a "flying wire" technique. At injection, the ORBUMP magnets keep the beam trajectory displaced by $\sim$ 4 cm with respect to the nominal beam orbit. The wire is placed between the displaced and nominal orbits. As the ORBUMP current decays back to zero, the beam moves back to the nominal trajectory, sweeping through the wire, and thus providing information about the transverse beam profile (in the bending –horizontal– view only). By recording the ORBUMP current and the response of the wire we can reconstruct the horizontal profile (the ORBUMP current translates very accurately to beam position). In order to control for which turn number the beam goes through the wire, we change the timing of the injected beam with respect to the time that the ORBUMP current rises, thus controlling for which turn number the measurement is made. There are two drawbacks in this method: first, the range is limited by the amount of time that the ORBUMP current stays on (about 30 turns equivalent), and second, since the injection timing with respect to the ORBUMP current plateau has to change to observe a different turn number, the measurements do not utilize the same beam, i.e if the width of turn number N is measured during a given cycle of the machine, turn N+1 can only be measured using one of the next cycles.

2.1. DC beam studies

This data set was obtained with the Booster running DC (rf system off and no ramping of the magnet power supplies). This was done in order to simplify the running conditions and reduce the number of parameters in the comparisons. To further reduce complications in the initial conditions, only a single turn worth of Linac beam was injected in the machine. The current of the Linac beam was controlled by detuning one of the Linac quadrupoles. Under

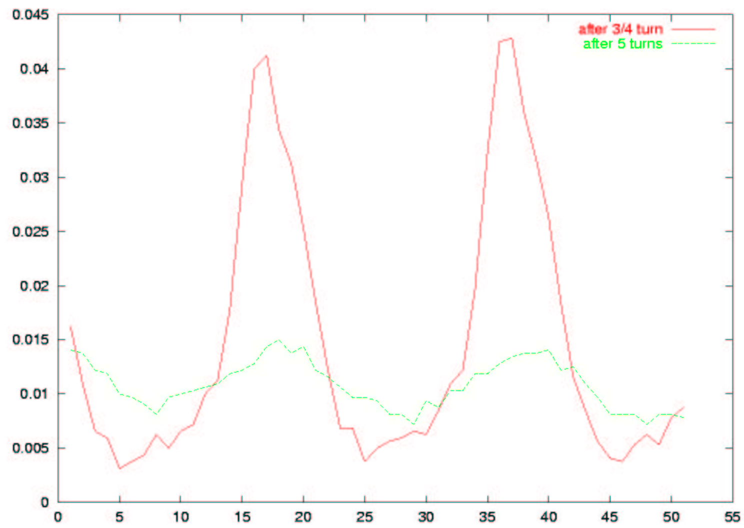

Figure 1. Beam current (arbitrary units) versus time/0.2×10^{-9} s from the RWM.

these conditions, we took data with injected beam of 11, 20, and 42 mA. A snapshot of two of the injected 200 MHz Linac bunches is shown in figure 1 3/4 turn after injection (the location of the RWM) and 4 and 3/4 turns after injection. The picture is from the 42 mA data set. Already, after $\sim$ 5 turns in the machine, the beam distribution in time is almost flat within the 200 MHz time slices. In figure 2 the RMS of the time distribution of the beam in a 200 MHz time slice is plotted versus the turn number. The data (points) is compared to the simulation (lines) for the different values of injected beam current. There is good qualitative agreement between data and simulation. The model predicts very small effects due to the different beam currents, well within the uncertainty of the measurement. Both the data and simulation extracted RMS widths tend to a constant value, since they are calculated within a 200 MHz time slice. Note that in the simulation we only model one 200 MHz bunch with periodic boundary conditions. This is an accurate representation of the main body of the beam (see discussion in [Amundson]). The $\Delta\ p/p$ used in the simulation was 0.2%. This value compares very well with the value 0.12% extracted from the decay of the beam's peak current as function of time, measured with the RWM; see figure 3. For this measurement the RWM was ran at low time resolution, in order to allow the observation of the beam for a long period of time. Because of that, the data set is not very clean, with aliasing effects and noise. The data is filtered (second curve in figure 3) and the time constant of the exponential decay of the peak current is extracted. This time constant is equal to the debunching time, dt/t, which relates to the momentum spread by $dp/p = (dt/t)/\eta$. For this data set, we only obtained transverse profiles with the IPM. A sample comparison is shown in figures 4 for the horizontal, and 5 for the vertical beam profiles, for a beam current of 11 mA. The beam was injected with an offset in both the vertical ($\sim -2mm$) and the horizontal ($\sim 7mm$). In both cases, the width of the beam, represented by the size of the bars in the plots, is well modeled by the simulation. Also, in both cases the IPM measurement of the mean of the beam is suspect, since it does not exhibit the expected oscillatory behavior (or if it does, it shows a very small amplitude). The simulation clearly exhibits the expected behavior. The other data sets, 20 mA and 42 mA beam currents, have the same characteristics.

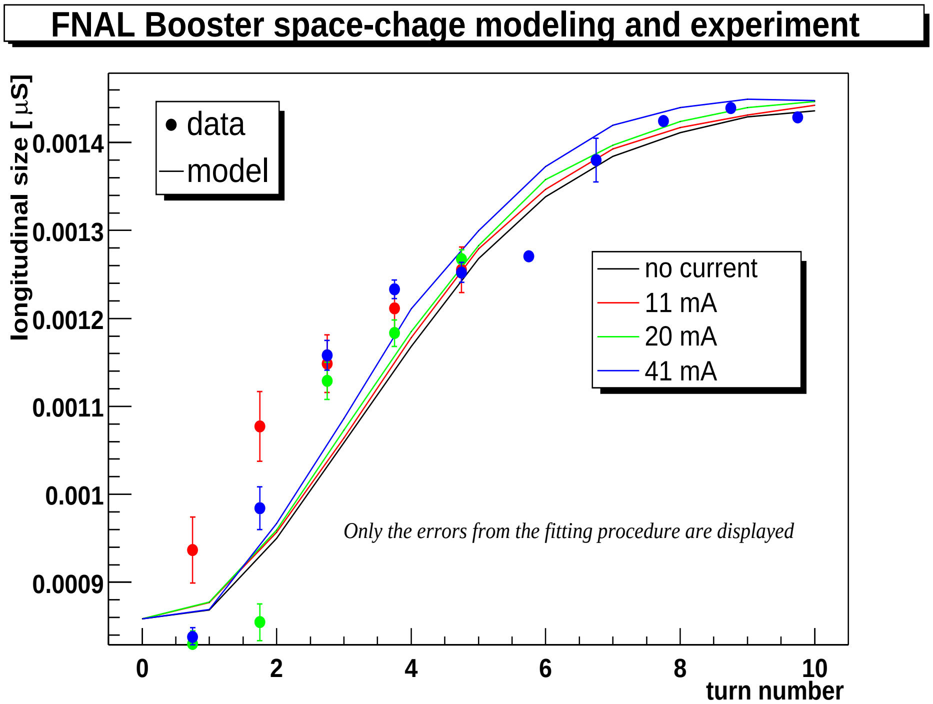

Figure 2. Longitudinal phase space evolution. Beam distribution RMS width in time as a function of turn number. The data from the RWM measurements (points with error bars) is compared to the model prediction from *Synergia* (lines).

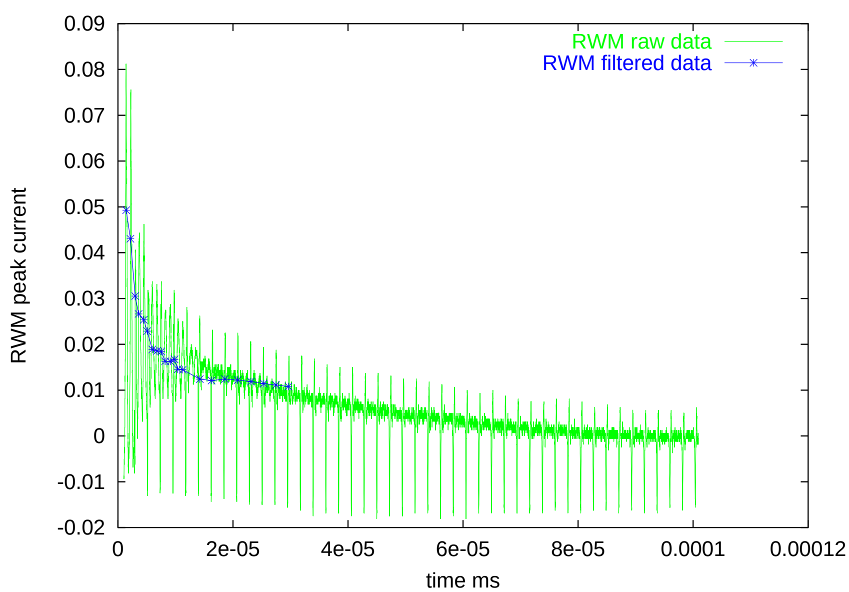

Figure 3. Peak beam current (arbitrary units) versus time/1×10^{-8} s from the RWM.

2.2. Multi-turn Injection Studies

This data set was obtained with the Booster cycling but with no net acceleration (the rf cavities were para-phased, i.e ran in pairs with equal and opposite phases). The beam from the Linac

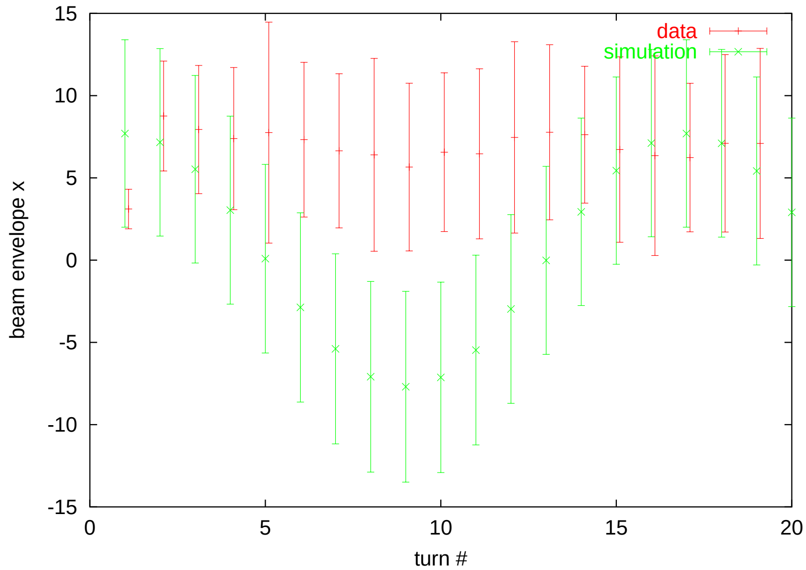

Figure 4. Horizontal beam width evolution as a function of turn number for beam current of 11 mA. The points represent the location of the mean of the beam while the size of the bars the width of the beam at this location. The IPM data are shown in red (points represented by a dash) and the model prediction in green (points represented by a star).

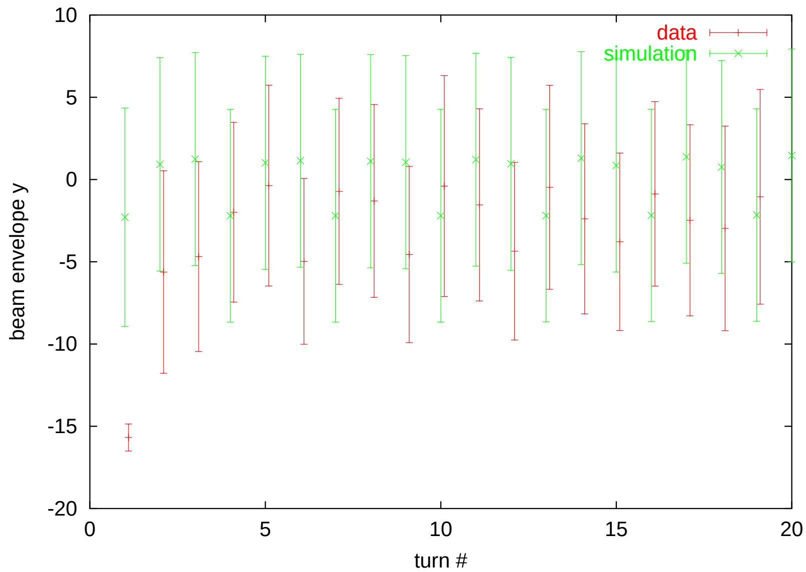

Figure 5. Vertical beam width evolution as a function of turn number for beam current of 11 mA. The points represent the location of the mean of the beam while the size of the bars the width of the beam at this location. The IPM data are shown in red (points represented by a dash) and the model prediction in green (points represented by a star).

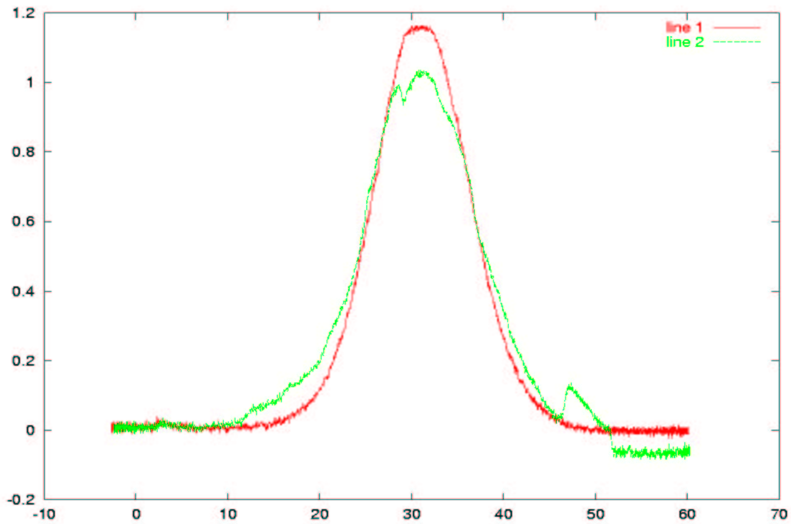

Figure 6. Sample of "flying beam" wire profile measurements. The horizontal axis is in mm. The red curve shows an example of a clean profile measurement, the green a case of a noisy one.

was injected in multiple turns. We collected data with one, five, and thirteen turn injection (13×40 mA beam current). No IPM data were taken, only "flying beam" wire data. An example of wire profiles is shown in figure 6. Most of the measurements were clean, like the one shown with the red curve in the figure. In some cases the data had additional "structure", such as the one shown with the green curve in the above figure. For all the data sets collected, the beam was injected with a 20% mismatch in x'. A comparison of data and simulation is shown in figure 7. The simulation qualitatively describes the data within the experimental uncertainty. The other data sets (different beam currents) have the same characteristics.

3. Summary

We have used *Synergia*, a beam dynamics package with 3D space charge capabilities, to model the FNAL Booster. We have collected data with the machine and compared the measured beam phase space evolution to the model prediction for the few first turns after injection. The model does a reasonable job describing the characteristics of the data in both the transverse and longitudinal coordinates. More work is needed (and is underway) to understand and cross-calibrate the instrumentation. The next step in this program will involve modeling and measurements of the beam parameters further into the machine cycle, where space charge effects are expected to be large.

References

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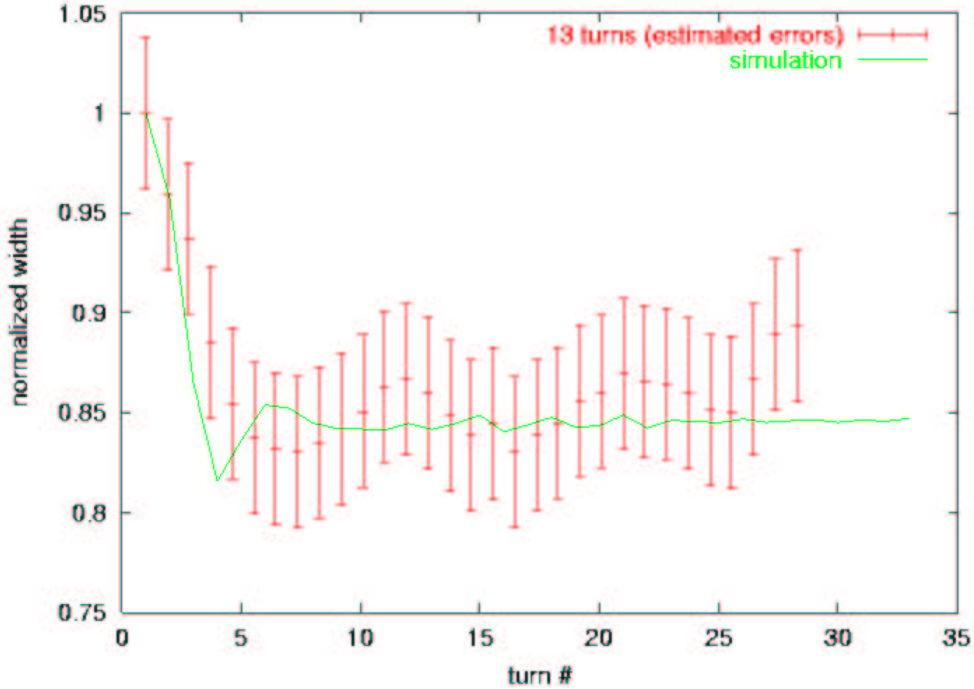

Figure 7. The normalized horizontal beam width (width divided by the width of the injected beam) versus turn number as measured with the wire (points) and extracted from the simulation (line). The error bars represent the estimated experimental error.

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